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The A_1 Problem, and Should SU(3) Multiplets be Complete*

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It is a fruitful and basic part of the lore of high energy physics that particle states are associated with interactions. This view has its origins in the identity of photon exchange with electromagnetic interactions, and in Yukawa's pion.

It now appears that this is not the situation for axial vector currents. The main axial vector state, the A_1, which would naively be expected, seems not to exist experimentally.

In this talk I want to: 1) briefly review the reasons for expecting certain axial vector states to exist (chiral symmetry, quark model, exchange degeneracy, ...), 2) remark on the (now rather compelling) evidence against the existence of the A_1, 3) tentatively explore some implications of the absence of the A_1 for sum rules, the quark model, ν reactions, etc. 4) comment briefly on SU(3) related axial vector states (Q, D. H), the possibility that SU(3) multiplets will not be complete because of symmetry breaking effects and dynamics, and a possible direction to look to understand which higher mass resonances exist.

This talk overlaps considerably but not completely with the talk I gave at the 10th Annual Recontre de Moriand .

1. REASONS FOR EXPECTING AXIAL VECTOR PARTICLES

a) At a qualitative level, we see evidence of vector interactions, such as the electromagnetic current, the weak vector current and CVC, and large exchange contributions of the appropriate quantum numbers in hadron two body reactions.

And, we have vector particles ρ, ω, ϕ, ...

Similarly, for the axial vector we have the weak axial vector current and PCAC. It is certainly justifiable to expect axial vector meson states.

b) Chiral Symmetry. Clearly nature shows evidence for some sort of chiral symmetry. It is reasonable to expect some implications for the spectrum of vector and axial vector mesons, and presumably some sort of symmetry in the particle spectra. The accepted answer since 1967 has been in terms of the Weinberg sum rules,

$$\int_0^\infty [\rho_V(m^2) - \rho_A(m^2)]\, dm^2/m^2 = f_\pi^2$$

$$\int_0^\infty [\rho_V(m^2) - \rho_A(m^2)]\, dm^2 = 0.$$

The ρ_V and ρ_A are the vector and axial vector spectral functions, and f_π is the pion decay amplitude, present because the axial current is not conserved. Single particle states appear as $\delta(m^2 - m_R^2)$ in the spectral functions. States of definite J^P and isospin are projected out. If these are saturated with ρ and an A_1, one gets $m_{A1} \simeq \sqrt{2}\, m_\rho$. This corresponds to the mass of the $\pi\rho$ enhancement observed in diffractive $\pi N \to (3\pi)N$ reactions. Thus the theory and data appeared to coincide and the naive expectations appeared fulfilled. But we must reconsider the situation if axial vector states do not exist.

Sum Rules

With J. Krisch and M. S. Chen (details will be published separately), I have looked at the Chiral Symmetry sum rules in some detail to see if any hints appear as to how to interpret things. At least we can make some measure of how bad local saturation with particle states seems to be.

Basically, one can proceed by noting that if sum rules are not saturated by single particle states, the integrands can be written in terms of scattering amplitudes. Essentially,

$$\delta(M^2-M_A^2) \sim \operatorname{Im} \frac{M\Gamma}{M^2-M_A^2-iM\Gamma} \sim \sin^2 \delta_{1+} \quad .$$

For example, it could have been that the $\pi\rho$ amplitude had a large imaginary part over a large range in $M_{\pi\rho}$ and so the vector and axial vector sum rules were comparably saturated in the low mass region.

In fact, we can estimate the phase δ_{1+} from the Illinois analysis. The experiment measures the relative A_1-A_2 phase. The part of the phase due to the production mechanism is approximately the same for A_1 and for A_2, because

(i) By comparison with charge exchange reactions, one can see that isoscalar and consequently even signature exchanges dominate.

(ii) The two processes are observed to have similar energy dependence

$$\sigma(A1) \sim p_L^{-0.4 \pm 0.06}, \quad \sigma(A_2) \sim p_L^{-0.51 \pm 0.05} \quad .$$

(iii) Whenever an even signature amplitude has a power behavior s^{γ} it has a phase $e^{-i\pi\gamma/2}$ by crossing and analyticity.

Thus the observed (Antipov, et al.) relative $\pi\rho$ phase can be interpreted as due to $\pi\rho$ scattering in the 1^+ and 2^+ partial waves, with the 1^+ phase shift constant at about 20^0.

Since $\sin^2 \delta \simeq 1/10$, the axial vector contribution to the sum rul es is suppressed by about an order of magnitudes.

The Chiral Symmetry is not locally satisfied. The V, A currents do not manifest themselves in similar ways in the sum rules. If the sum rules are satisfied, it is in a way which is not symmetric as far as the low energy parts are concerned.

c) Quark Model. In the quark model the $L = 0$ $q\bar{q}$ mesons with $S = 0, 1$ are π and ρ (concentrating on isovectors). With $L = 1$ one has the B (which exists) with $S = 0$ and A_2, A_1, and $J^{PC} = 0^{++}$ states with $S = 1$. Thus here we not only expect A_1, it is somewhat hard to imagine the quark model without it. One thing to try for the quark model is to modify mass predictions from their standard values to put the A_1 at a very high mass. It is not easy. One could write

$$M^2 = M_0^2 + M_1^2 \vec{s}_q \cdot \vec{s}_{\bar{q}} - M_2^2 \vec{S} \cdot \vec{L} \ .$$

The eigenvalues of $\vec{s}_q \cdot \vec{s}_{\bar{q}}$ are $1/4$ for $S = 1$ and $-3/4$ for $S = 0$ (π, B). The eigenvalues of $\vec{S} \cdot \vec{L}$ go as $1, 0, -1, -2$ for A_2, B, A_1 and 0^+ states. Presumably the A_2 and B masses can be put in. That leaves one free mass. Note the sum rules

$$M^2_{A1} + M^2_{A2} - 2M^2_B = 8M^2_1$$

$$M^2_0 = M^2_{A1} + (M^2_{A1} - M^2_{A2})/2 \ .$$

Since M^2_1 is presumably constrained to give the π-ρ splitting too, it cannot allow M^2_{A1} to get very large, from the first of these. The second tells us that if we wish the scalar meson states in the mass range below the A_2 to have anything to do with quark model 0^+ states than $M_{A1} < M_{A2}$. So far I have not seen any way the quark model spectroscopy can function without an A_1. It is not easy to see how constituent quark models can survive the absence of an A_1 without basic modification.

d) Exchange Degeneracy and Duality. The spectrum of dual models requires an A_1 (see P. Frampton, Phys. Rev. Lett. 34, 840 (1975)), but there is not a single clean way to see that it must be required. It is possible to imagine that from the duality viewpoint an A_1 is desirable but not basic.

2. Comments on the Experimental Situation

a) Nondiffractive Reactions. To decide the experimental situation there are two possibilities, given the present state of affairs.

(i) an A_1 if found in a nondiffractive reaction.

(ii) an A_1 is not found in a nondiffractive reaction.

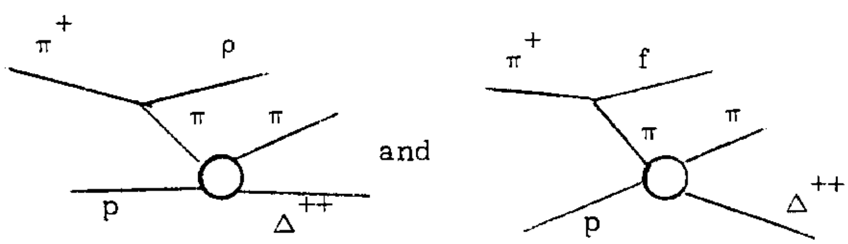
To give meaning to case (ii), it is necessary to know at what cross section level an A_1 should have been found. Typical nondiffractive reactions are $\pi^+ p \to A_1^0 \Delta^{++}$, $\pi^- p \to A_1^0 n$, $\gamma p \to A_1 N$, $\pi^- p \to p A_1^-$ (backward), $K^0 p \to A_1^0 \Lambda$, etc.

At the moment there is only a useful limit published from $\pi^+ p \to A_1^0 \Delta^{++}$. To estimate the A_1 cross section produced by ρ exchange, one needs to know essentially standard two-body technology, plus the $A_1 \rho\pi$ coupling. The latter depends on an overall size which gives the width, and a relative parameter which can be thought of as the ratio of D to S coupling, or the amount of helicity zero vs. helicity one.

The LBL experiment analyzed by Wagner, Tabak, Chew gives $\sigma(A_1) < 2$ μb after a partial wave analysis, for $\Gamma(A_1) = 150$ MeV, at 7 GeV/c. Using A_1 couplings from typical models gives an expected cross section of 36 μb, while calculating the minimum possible cross section for any D/S coupling ratio gives 4.5 μb. The observed signal is significantly below even the minimum cross section.

A similar and probably eventually better limit comes from the same reaction, $\pi^+ p \to (\rho\pi)^0 \Delta^{++}$, at 15 GeV/c (C. Baltay, private communication). The experimental limit is $\sigma(A_1) < 1$ μb, just from statistics, before a partial wave analysis is performed. We expect 15 μb for standard couplings, and 2 μb for the minimum cross section for any coupling.

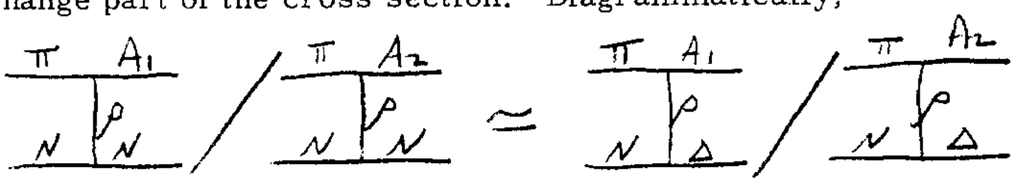
There will necessarily be a charge-exchange Deck model background from



with threshold peaks above the $\rho\pi$ and $f\pi$ thresholds. These should give cross sections of about 1 μb at 7 GeV/c and 1/2 μb at 15 GeV/c. To get better limits than these levels it will be necessary to do a Deck subtraction. Signals at these levels should be interpreted as Deck background, not repeating the situation in the diffractive case where they were first thought to be resonances.

It should be emphasized that the Deck background will give bumps at $\rho\pi$ and $f\pi$ thresholds (about 1100 and 1450 MeV respectively), and that <u>normalized</u> estimates are necessary to conclude a signal has been seen.

Soon data will be available for $\pi^- p \to$ "A_1^0" n. It should be noted that there is an approximate factorization constraint, for the natural parity exchange part of the cross section. Diagrammatically,



and so

$$\sigma_{NP}(\pi^{\pm} N \to A_1^0 N)/\,\sigma_{NP}(\pi^{+} N \to A_2^0 N) \simeq \sigma_{NP}(\pi^{\pm} N \to A_1^0 \Delta)/\,\sigma_{NP}(\pi^{\pm} N \to A_2^0 \Delta) \equiv r$$

The LBL 7 GeV/c and the Colombia 15 GeV/c experiments see r < 1/10, so the experiments with a final nucleon must see r < 1/10, if the data is consistent. If they do not then it is necessary to understand why the approximate factorization fails before the situation can be interpreted. The experiments with a recoil Δ are bubble chamber ones which have no bias problems and which see an A_2 signal and no A_1 signal, so it is very hard to see a way they could go wrong.

b) Diffractive Reactions. Here we want only to note that the Deck model threshold enhancements are expected to occur, giving large bumps at about 1100 and 1450 MeV for $\rho\pi$ and $f\pi$, even in the 1^+ partial wave. It is important to make normalized, absorbed, model-dependent estimates for this effect over the entire low mass region.

Since any diffractive $\pi^+\pi^-\pi^0$ production will include the large and structured Deck background, it will be very difficult to draw a negative conclusion about the A_1 existence from looking at diffractive data.

3. SU(3) Multiplets and Other Axial Vector States

In this section two related questions are briefly discussed, (i) If some axial vector states such as D or Q exist, does that suggest the A_1 does? (ii) Should SU(3) multiplets be expected to be complete or can missing particle states be expected as a form of symmetry breaking?

I think the answer to (i) is in terms of the notion of "Accidental Particles" introduced by Dashen and myself (Phys. Rev. , Jan. 1975). Basically, the idea is that some particles (e.g., π, ρ, N, Δ, ...) will exist for "fundamental" reasons (e.g., the quark model or bootstrap, or whatever). Once these exist, strong forces act between them, and occasionally rearrange the density of states in some channels, producing a resonance, an "accidental particle". Averaged over 200-300 MeV there is no net increase in the number of states because the rise of the phase shift through $\pi/2$ is compensated by a decrease back to zero. The deuteron is a very good example of this. One then expects because of SU(3) breaking in the basic multiplets that the accidental particles will not generally come in complete SU(3) multiplets. For example, the deuteron is bound by the strong long range π exchange force, while the forces due to heavier K, η exchanges are not strong enough to bind the other members of a deuteron multiplet. Probably for hadrons the main forces are strongly coupled inelastic channels.**

Consider the axial vector isoscalar states D and H(G = -1) from this point of view. For the D (ignoring strange particle and baryon channels) one has πA_2, ηf, $\rho\rho$, $\omega\omega$ channels coupled, and $\pi A_2 \to f\eta$, $\pi A_2 \to \rho\rho$, $\rho\rho \to \omega\omega$ are all strongly coupled by π exchange. On the other hand, for the H only $\pi\rho$ and $\eta\omega$ are coupled and they are not coupled by a long range π exchange force. Thus, it is much more probable that the D should exist as a result of the strong interactions than that H should, and that is what is observed. If this viewpoint is basically correct then the existence of the D does not have implications for the A_1.

Whether any meaningful quantitative calculations can be done from this viewpoint is unclear, but we are in the process of trying to develop a systematics that will allow useful discussions.

Perhaps such an approach will be able to explain why some states are present and not others. In some sense, yet to be made quantitative, the fundamental interaction gives the low lying states but it should be thought of as a potential or a driving mechanism. Then which higher states will exist is determined as a combination of the structure of the "potential" and of unitarization. For the mesons maybe it would work out that A_2, B, D exist but not B, H. For baryon states maybe some Z^*'s and maybe the Roper resonances $N^*(1470)$ are accidental and should not go into full multiplets nor have important symmetry consequences. It will be very useful if a systematic way can be developed to address these questions.

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** Compelling analyses for a number of years have shown that inelastic coupled channels were very effective in producing resonances. Work by Cook and Lee, Carruthers and especially Aaron and Amado and collaborators has been done, mainly on πN reactions. Our approach is not to argue that the mechanism is important, which we regard as established, but that it may be much more important, especially for symmetry breaking questions, than has been realized. The first applications of the inelastic channel mechanisms to produce Z^*'s and to SU(3) was by J. J. Brehm and G. L. Kane, Phys. Rev. Lett. 17, 764 (1966). A number of related subjects are discussed and reviewed in the proceedings of the Purdue Baryon Resonance Conference. (I would like to thank R. Cutkosky for pointing out this useful source.)